Radioisotope Power Systems Program Status and Expectations

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The NASA Radioisotope Power Systems (RPS) Program's goal is to make RPS available for the exploration of the solar system in environments where conventional solar or chemical power generation is impractical or impossible to use to meet mission needs. To meet this goal, the RPS Program manages investments in RPS system development and RPS technologies. The RPS Program exists to support NASA's Science Mission Directorate (SMD). The RPS Program provides strategic leadership for RPS, enables the availability of RPS for use by the planetary science community, successfully executes RPS flight projects and mission deployments, maintains a robust technology development portfolio, coordinates RPS related National Environmental Policy Act (NEPA) and Nuclear Launch Safety (NLS) approval processes for SMD, maintains insight into the Department of Energy (DOE) implementation of NASA funded RPS production infrastructure operations, including implementation of the NASA funded heat-source plutonium production restart efforts. This paper will provide a status of recent RPS activities and accomplishments.

Nomenclature

APL	=	Applied Physics Laboratory
ATR	=	Advanced Test Reactor
DCT	=	Dynamic Convertor Technology
DOE	=	Department of Energy
DRPS	=	Dynamic Radioisotope Power Systems
EMD	=	Environmental Management Division
GPHS	=	General Purpose Heat Source
GRC	=	Glenn Research Center
HFIR	=	High Flux Isotope Reactor
HSMRTG	=	Hybrid-Segmented-Modular Radioisotope Thermoelectric Generator
INL	=	Idaho National Laboratory
LWRHU	=	Light-Weight Radioisotope Heater Unit

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MMRTG = Multi-Mission Radioisotope Thermoelectric Generator
NASAS = National Aeronautics and Space Administration
NEPA = National Environmental Policy Act
NLS = Nuclear Launch Safety
NLSA = Nuclear Launch Safety Analysis
ORNL = Oak Ridge National Laboratory
OSI = Office of Strategic Infrastructure
OSMA = Office of Safety and Mission Assurance
PD/NSC-25 = Presidential Directive/National Security Council Memorandum #25
PSD = Planetary Science Division
RFP = Request for Proposals
RPS = Radioisotope Power Systems
RTG = Radioisotope Thermoelectric Generator
SMD = Science Mission Directorate
SMRTG = Segmented-Modular Radioisotope Thermoelectric Generator
SMT = Surrogate Mission Team
SRTG = Segmented Radioisotope Thermoelectric Generator
TE = Thermoelectric
W_e = Watts electric

I. Introduction

The National Aeronautics and Space Administration (NASA) Radioisotope Power Systems (RPS) Program exists to provide solutions for the power demands of U.S. robotic planetary science missions to deep space and the most extreme environments in the solar system. NASA considers the use of RPS for missions where it would be impractical or impossible to use conventional solar or chemical power generation to meet mission needs. The goal of the RPS Program is to make RPS available to meet this need by managing NASA investments in RPS system development and RPS technologies, in a close partnership with the Department of Energy (DOE).

Significant progress and some fundamental changes to the content occurred within the RPS Program in 2016. The RPS Program content was expanded to include coordination of the RPS-related National Environmental Policy Act (NEPA) and Nuclear Launch Safety (NLS) approval processes. This change will provide for the management of the required processes in the Program rather than with the individual missions, with an end goal of streamlining processes for missions while maintaining safety and environmental policy requirements. The Program has also recently finished a study that focused on defining the investment strategy toward development of future thermoelectric-based RPS. This strategy will inform investments within the RPS Thermoelectric Technology Development Project and within the Program's Systems Formulation and Mission Integration area that could culminate in the development of a new Radioisotope Thermoelectric Generator (RTG) to support NASA's Science Mission Directorate (SMD) goals. The program also updated its investment strategy for dynamic power systems; the revised path provides for the development of different dynamic cycle convertors that could possibly lead to a dynamic RPS development with DOE. In addition, the RPS Program collaborated with DOE to consider implementing

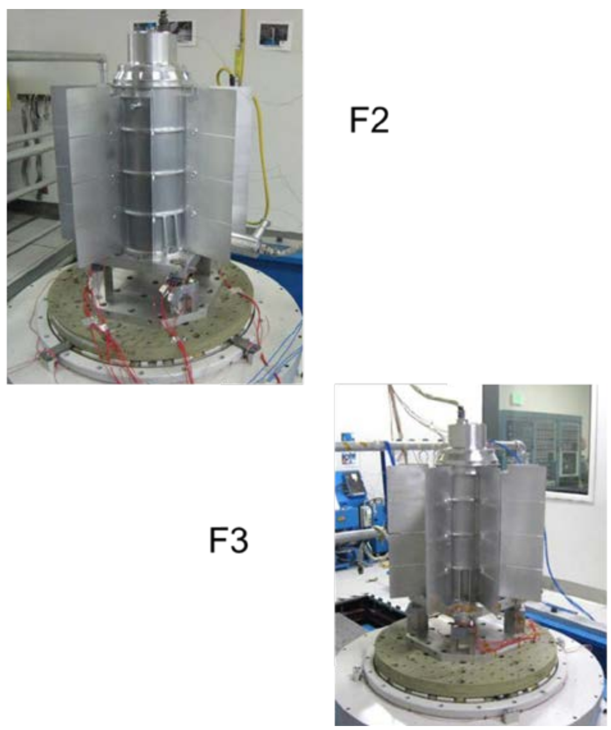

Figure 1. MMRTG F2 and F3 Flight Units being processed for Mars 2020.

a constant-rate production strategy. This strategy would allow for NASA-provided funding to DOE to be used to increase the reliability of radioisotope power systems production capability and increasing the availability of RPS for potential use on future missions. These changes are being considered while the RPS Program continues its direct support to RPS-enabled missions. The RPS Program, via agreement with DOE, is providing one flight-ready Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), seen in Fig. 1, to NASA's Mars 2020 mission. After Mars 2020 launches, one remaining MMRTG will be available to support a future mission. This unit, along with the potential for two additional MMRTGs can be provided to support a New Frontiers-4 mission concept if required. DOE has the ability to produce additional MMRTGs beyond those that could be produced for a New Frontiers-4 mission concept, if NASA requires.

II. RPS-related NEPA and NLS Approval Processes

RPS missions require compliance with the National Environmental Policy Act (NEPA), Presidential Directive/National Security Council Memorandum #25 (PD/NSC-25), and the 2010 National Space Policy. The NASA NEPA program is managed by the Office of Strategic Infrastructure (OSI), Environmental Management Division (EMD). The NASA Office of Safety and Mission Assurance (OSMA) manages NASA's Nuclear Launch Safety Analysis (NLSA) process and plays a lead role in completing the PD/NSC-25 process. RPS are built and delivered by DOE for NASA missions. Safety is a core consideration for NASA and DOE and is infused throughout the system lifecycle, with a focus on the protection of the public, the environment, workers, property, and other resources from undue risk of injury or harm. This lifecycle approach is ubiquitous throughout the process of designing, building, and testing RPS, resulting in a product with multiple layers of safety in the RPS generators and comprehensive underlying analysis that provides confidence that the system—when integrated with the spacecraft and launch vehicle—is safe for launch. This analysis undergoes an interagency review before any proposed launch is submitted to the Executive Branch for final consideration of launch approval.

In 2016, SMD directed the RPS Program to coordinate the NEPA and NLS efforts for RPS Missions. The Program will be responsible for coordinating NEPA and NLS activities for missions that propose to fly RPS power and for development of multi-mission products in support of NLS to support missions launching after NASA's Mars 2020 rover (which will use one MMRTG). These activities are currently managed by the individual Program Executives for the mission that would use an RPS. Utilizing the RPS program office on behalf of the Program Executive provides for a more consistent approach to this activity, as Program Executives may not remain constant with RPS missions. The scope of this area includes all aspects of RPS NEPA compliance and launch nuclear safety on behalf of NASA SMD, in cooperation with NASA EMD and OSMA for RPS-based missions. The DOE continues to conduct specific activities associated with nuclear launch safety as required by U.S. National Space Policy. These analyses require NASA inputs and support. The RPS Program ensures the proper coordination of efforts across these organizations. Focusing coordination of mission activities within a single program will better facilitate the potential application of RPS power and/or use of Light Weight Radioisotope Heater Units (LWRHUs) to meet the needs of future missions.

The processes that have been developed and employed to comply with environmental requirements and the assessment of launch nuclear safety are continually updated to identify any improvements that should be considered. To that end NASA conducted an internal two-year review of past and current environmental compliance and safety analysis processes and of the mission specific data that has been generated. At the time of this writing, these data are being reviewed to determine if any changes are merited.

With the increasing consideration of Smallsats and Cubesats mission concepts for planetary exploration, more compact RPS may be required, and an understanding of the best approach to mission safety compliance for these missions that could require much smaller quantities of radioisotope fuel is being considered. In cases where power levels required would be less than one watt, other isotopes may be considered for application and, if pursued, the safety analysis bases for these isotopes would need to be established.

III. Next Generation RTG Study

In early 2017, the RPS Program completed a study of potential next-generation Radioisotope Thermoelectric Generator (RTG) needs, focusing on advancing the capabilities of thermoelectric-based RPS-powered mission concepts. The objective of this study was to determine the characteristics of the next RTG that would "best" fulfill the future directions of NASA's Planetary Science Division (PSD). This study was limited to systems that convert heat to electricity using thermoelectric couples. "Best" was defined as a confluence of the following factors: 1) an RTG that would perform effectively throughout the solar system; 2) an RTG that maximizes its utility across a variety of mission types: flyby spacecraft, orbiters, landers, rovers, boats, submersibles, and atmospheric craft; 3) an RTG that would have reasonable development risks and a workable timeline; and 4) an RTG would result with sufficient value

(importance, worth, and usefulness) returned to PSD for the resources that would be invested, as compared with retaining the existing baseline system (the MMRTG). The study looked at most foreseeable destinations within the solar system to inform the program of the potential new system and technology investments needed to support the system development. The outcome of the study also provided top-level initial requirements.[1]

The multi-NASA center, multi-organization study team followed the approach in Fig. 2. This approach considered past missions studies, current thermoelectric technologies, and current and past RTG designs and concepts to uncover the most significant requirements drivers. These top-level requirements were then used to develop a variety of RTG concepts. These concepts were then used by NASA Goddard Space Flight Center's Mission Design Lab to create a design reference mission used to compare the benefits of the generator concepts. The concepts were also provide to the Johns Hopkins University Applied Physics Laboratory (APL) and to NASA Glenn Research Center (GRC) to evaluate how the concepts would integrate into past studies or missions, such as GRC's Titan Submarine mission concept [2,3] and APL's Pluto New Horizons mission.[4] The result of all of this work was documented in a final report.[5]

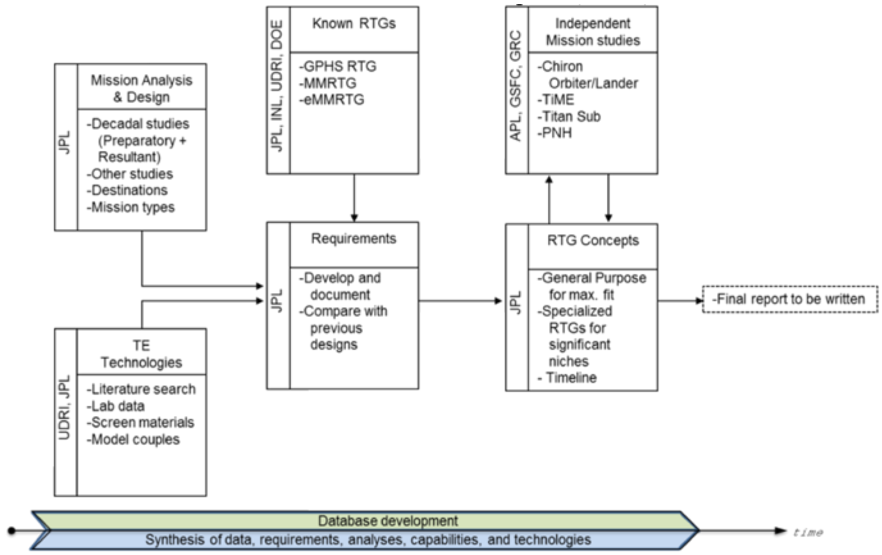

Figure 2. Next Generation RTG Study Approach.

The study's mission analysis and design work reviewed over 200 mission concepts that have been developed over the years by the NASA science community, including flyby and orbiters. The concept study set also included atmospheric probes, landers, rovers, aerial spacecraft, and floating and submersible craft. All of these mission ideas were entered into a searchable database. This database provided and easy way to consider all types of potential mission drivers on RTG requirements. One important consideration to maximize the ability of a Next-Generation RTG to serve a multitude of mission concepts was the need for system flexibility. The team addressed this flexibility by conceptualizing a modular RTG that would allow a mission concept to choose the appropriate power level that would meet its need. Such a modular approach considers the number of General Purpose Heat Source (GPHS) modules that could be used to fuel the generator. Modules of two were considered, and the resulting power system concepts ranged from a two-GPHS system to a sixteen-GPHS system. Other considerations that were uncovered were the need to have generators that were optimized for cold environments, and systems that were optimized for destinations that have an atmosphere or for vacuum.

To accommodate these considerations, the study investigated three new generator concepts, two of which were modular based, and a variant of each that were optimized for cold environments. These optimized concepts were determined to not be beneficial enough to pursue. A modular concept that would operate only in vacuum, called the Segmented-Modular RTG (SMRTG), was studied. A modular concept that features a sealed housing and could operate both in vacuum and in an atmosphere, called the Hybrid-Segmented-Modular RTG (HSMRTG), was also studied. The term "segmented" refers to the segments in the notional thermoelectric (TE) couple, ranging from one to three segments. Lastly, a non-modular concept called the Segmented RTG (SRTG) was considered. All of the generator concepts assumed a common thermoelectric building block that could be comprised of various advanced TE materials. The TE materials considered were packaged in one, two or three couples, resulting in TE couple efficiencies from approximately 11% to 17 %, with predicted degradation rates that would result in a reduction in power of 1.9% per year. This rate includes the projected rate of decay of the fuel. Over 30 different couple configurations were modeled. Combining the different TE couples with the different types of generators resulted in over 200 different possible combinations. The ability for the systems to meet mission needs, combined with the technology readiness levels of

the material and the technology readiness levels of the proposed couples, were used to identify a path to a Next-Generation RTG.

The RPS Program, working with NASA Headquarters and the lead of the Next-Generation RTG study team, reviewed the mission studies, the thermoelectric couple material options and the system concept data to develop the top driving requirements for a next-generation RTG. These requirements seek to result in a modular system designed for vacuum operation that, when using 16-GPHS, would provide at least 400 We, with a goal of 500 We, when the system is first fueled. The system degradation rate goal, including the fuel degradation, would be 1.9% per year, comparable to that of the GPHS-RTG used on missions such as Cassini. The system mass goal would be 60 kg or less.

The RPS Program is working with DOE and the TE Technology Development Project to develop a path that would mature the TE technology for insertion into a new generator design. A phased approach will be implemented that will involve industry participation and knowledge transfer. The initiation of this work is anticipated in 2018.

IV. Dynamic RPS Status

NASA is interested in the development of dynamic energy conversion, primarily due to the potential for significant increases in conversion efficiency. The current flight RPS, the MMRTG, produces ~110 We at the beginning of a mission, at a system conversion efficiency of about 6%. NASA is seeking higher-efficiency conversion technologies that are reliable and robust, with long design life. These conversion technologies, once developed, can be beneficial to an RPS and other types of thermal-to-electrical power conversion systems that are being considered by NASA.

To develop these convertors, the RPS Program, working with the DOE, is conducting two major efforts: one that matures the dynamic technology of the convertors, called Dynamic Convertor Technology (DCT), managed under the Program's Stirling Convertor Technology Project; and, another that grounds the technology maturation from a mission and system perspective, called Dynamic RPS (DRPS) engineering, managed under the Program's Systems Formulation and Mission Integration function.[6] Key activities of this work includes 1) a procurement activity intended to result in a design and breadboard level of hardware, 2) the establishment of a Surrogate Mission Team (SMT) to develop generator system and interface requirements, and perform engineering system trades, 3) engagement with industry to assess technologies to understand the technology readiness and risks to consider for a near-term flight development activity, and 4) an activity that evaluates the use of the convertors within RPS concepts. NASA and DOE are examining these general concepts; however, a specific dynamic generator is not being designed. Concepts are being evaluated to help NASA determine how the convertor technology could impact the generator requirements. This will better inform NASA and DOE decision makers on the final set of system requirements for a dynamic RPS. The current power range of interest is approximately 200 to 500 We.

In 2015, the RPS Program released a Request for Information to understand the state-of-the-art of Stirling conversion technology, followed by a Request for Proposals (RFP) in 2016 seeking to mature dynamic conversion technology through funding of multiple technology investments. NASA decided to open the range of conversion technologies in the RFP to options greater than just the Stirling cycle, with the intent to inform potential future development efforts. Examples of potential dynamic conversion technologies include Brayton, Stirling, and Rankine cycle machines. Dynamic conversion methods offer the potential for higher conversion efficiencies, but have yet to be demonstrated in a long-life spaceflight application. The goal of this effort is to investigate dynamic conversion technology options suitable for use in a power system that would use the current GPHS Step 2 modules as a heat source. The intent is to gather data on candidate dynamic conversion technologies to fill knowledge gaps, support assessments of dynamic conversion technologies, and elicit generator requirements. This effort focuses on the conversion technology itself, the technology required to operate the convertor (i.e., controllers), and the thermal management necessary to operate the convertors. NASA will lead management of this convertor technology investigation while collaborating with DOE.

A three-phase process has been put in place. Phase I will focus on the selected contractors developing a convertor design. At the end of Phase I, a joint NASA and DOE independent review will be held to evaluate the designs against the requirements. Designs that proceed to Phase II would undergo hardware development and testing. At the end of Phase II, the hardware will be delivered to NASA and more testing will be conducted during this final Phase III. At the end of Phase III, a final independent review will be held to determine if the technology is mature enough and the development risks are well-enough understood that subsequent development of a generator is deemed practical and necessary. Phase I is to begin with the contact awards in the July 2017 timeframe and Phase III will be completed late 2020.

V. Constant Rate Production

NASA and DOE continue to collaborate on methods to ensure the capability and stability to develop, manufacture, and deploy RPS is available to meet future space exploration needs. Currently, the agencies are pursuing a "constant-rate production" strategy that would put a greater emphasis on establishing interim production levels of new Pu-238 heat-source material, with the short-term goal being to average 400 g/year by 2019, and a long-term goal to obtain an average rate of 1,500 g/year by 2025. By implementing this approach, NASA and DOE would anticipate a reduction in mission supported funding resulting from the cyclical nature of approved RPS missions. Such a reduction would provide the ability to maintain consistent staffing levels, invest more effectively in equipment maintenance and refurbishments, better evaluate process improvements, and provide a ready supply of RPS heat sources ready for mission use. As part of this strategy, emphasis will be placed to improve integration along the supply chain to reduce time constraints on mission launch schedules.

Previously, DOE maintained the ability to process heat-source plutonium fuel into cladded pellets for incorporation into GPHS modules by pressing and cladding a small number of pellets each year, and placing these into storage or using them in safety test or analysis applications. This "minimal sustainment" approach was not scaled to allow for the production runs necessary to support a flight mission, and necessitated increases in staff and other considerations when production for a mission became required. This resulted in higher costs during the production period that were passed on to the mission requiring the RPS. These costs could be significant to a mission and also made the mission vulnerable to the risks associated with potential interruptions in production due to things like equipment failure, and recruiting and training of highly-specialized staff.

The new constant-rate production strategy provides for the fabrication of fuel clads in annual quantities that allow the creation of a known inventory sufficient to meet planned mission needs, without mission-driven adjustments in staff and equipment. Pu-238 half-life is sufficiently long that the stockpiled fuel clads will have shelf-lives long enough to maintain GPHS heat output specifications as currently required.

In addition to processing the fuel, DOE has been working to reestablish the domestic production of heat-source plutonium for NASA missions. Before NASA and DOE established the constant-rate production model the effort to reestablish this production capability was treated as a segmented project. This segmented management approach was replaced with a model utilized by DOE's Oak Ridge National Laboratory (ORNL) to produce other isotopes. The new strategy positions the RPS infrastructure to support a level of sustained production of certain components consistent with NASA requirements. Constant-rate production focuses on long-lead components that support production of heat-source material, heat sources (fueled clads), specialized materials, and placing fueled clads into a stable configuration for storage at DOE's Idaho National Laboratory (INL). Inherent in this approach is the evaluation of capabilities, risks, and opportunities across the supply chain to ensure reliability and stewardship of assets and the environment. All aspects of the supply chain, such as plutonium load-out capabilities at ORNL, optimizing Pu-238 production at INL's Advance Test Reactor (ATR) and ORNL's High Flux Isotope Reactor (HFIR), and accelerating research on the new target designs, are being evaluated. In addition, efforts are underway to develop a maintenance strategy to improve the reliability and predictability of operations.

VI. Conclusion

The RPS Program continues to support NASA's current, emerging and potential planetary missions in a variety of evolutionary ways. Continual progress in conversion technologies are allowing for long-range investments to develop systems that are more efficient and better suited to meet the challenging needs of potential future missions. NASA and DOE are making strategic changes to the approaches used for technology investment, supply chain management, and cross-agency coordination, to ensure that RPS are available for NASA's current and future mission needs. These changes should result in more consistent, predictable, and lower mission costs, and a program that is potentially more adaptable to the evolving needs of the mission design and scientific communities, while maintaining the safety philosophy and processes that have contributed to NASA's strong record of safe use of RPS for the past five decades.

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